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Fatigue crack growth testing using varying *R*-ratios

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Abstract

A method to generate high temperature fatigue crack growth data for multiple *R*-ratios during a single or only a few tests for surface crack specimens was developed. Two tests were performed; one with $0 \leq R \leq 0.8$ and one with $-1 \leq R \leq 0$. The crack growth was monitored using the potential drop method. It was shown that the results from tests with varying *R*-ratio gave very similar results to test with constant *R*. Fatigue crack growth predictions with data from varying *R*-test were generally slightly more conservative compared to predictions using data obtained from conventional testing.

Keywords: Fatigue crack growth; Experimental techniques; *R*-ratio;

Nomenclature

a,c	crack length at deepest point and at the surface, respectively
$A_{0\text{-}3}$	parameters in the NASGRO™ crack growth equation
C,n,p	constants in the NASGRO™ crack growth equation
$\mathrm{d}a/\mathrm{d}N$	fatigue crack growth rate
f	crack opening function
K	stress intensity factor
R	load ratio
α	constraint factor in the NASGRO™ equation
$\Delta K, \Delta K_{th}$	stress intensity factor range and threshold stress intensity factor range
σ	nominal (far field) stress
$\sigma_{\max}/\sigma_0$	ratio of maximum strain to flow stress (average of yield and ultimate tensile strength)

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1. INTRODUCTION

The fatigue crack growth (FCG) rate is commonly expressed as crack increment per cycle, da/dN, as a function of the stress intensity factor range ΔK. The stress intensity factor incorporates the effects of applied stress, σ, specimen geometry and crack length, a. However, for the same value of ΔK the FCG rate will vary with the R-ratio:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{1}$$

Conventionally, the R dependence of a material is determined by testing multiple samples, each with a constant R-ratio, resulting is a both time and material consuming procedure as each specimen has to be machined instrumented, set up and pre-cracked. Recently, Tesch *et al.* [1] suggested a method where the da/dN-ΔK relationship could be determined for multiple R-ratios using a single specimen. The method consisted of a series of successive constant K_{max} test, where K_{max} was increased between each block and K_{min} was ramped during the block. Thus, the span of R-values defined by K_{max} and the ramped K_{min} were continuously swept through in each block. The result can be analyzed to give the da/dN-ΔK relationship for any value R between the extremes defined by the specific test, as well as the threshold levels for certain R-values. However, the method needs rigorous treatment and transformation of the experimental data to arrive at the final da/dN-ΔK behavior. Kujawski *et al.* [2] proposed a different method which, similar to [1], consists of several consecutive constant K_{max} tests where K_{min} was either increased or decreased in steps, leading to discrete values of R. This method is easier to perform than the method in [1], but the drawback is that data is only obtained at pre-defined R-values and no threshold levels are obtained.

One problem with the methods discussed above is that they are both on specimen geometries which allow large crack length increments, such as M(T) specimens with width 160 and 320 mm [1] and single-edge notched specimens with a width of 44.4 mm [2]. In many industrial applications however, the specimen geometry is dictated by other factors, such as pre-defined lifing methodology, high temperature equipment or other test related issues. The present paper aims to evaluate a technique utilizing the varying R approach to determine the R-dependence of the FCG behavior using a specimen geometry allowing only very limited clack length.

2. EXPERIMENTAL

The material was obtained from a round bar of Inconel 718 with a diameter of 25.4 mm. Kb-type surface crack specimens with cross-section 4.3x10.2 mm were used, with an EDM machined notch of nominal depth 0.075 mm. The pre-crack was generated at room temperature with 10Hz and R=-1 to an approximate size of 0.4 mm. The crack length, a, was monitored using the direct current potential drop (PD) technique according to ASTM E647 [3]. The PD signal was measured every 10 cycles and translated to crack length by normalizing the PD signal measured over the crack witha reference PD signal from an un-cracked region of the specimen and an experimentally determined calibration curve. The recorded data was post-filtered using an 11-point running average. The filtered crack lengths were rounded to 0.01 mm (resolution of the PD technique) and the cycle number N_i corresponding to rounded crack length a_i was calculated as the average of the number of cycles associated with the crack lengths rounded to a_i. The stress intensity factor was calculated according to ASTM E740 [4] assuming a semi-circular crack and the FCG rate was calculated using the secant method [3].

The maximum crack length allowed in Kb-type specimens is in the order of 2.5 mm which restricts the choice of loading spectrum. The philosophy in the present method was to obtain data points at a minimum of three levels of ΔK for each value of R, distributed with some spacing in ΔK, to allow regressions to be made. To achieve this, the maximum load, P_{max}, was constant during the tests and P_{min} was changed in both increasing and decreasing steps to obtain data at pre-defined R-values. The method is essentially a combination of the two test methods in [2] (with increasing and decreasing ΔK) but without stepping P_{max}.

Two specimens were tested at a frequency of 0.5 Hz at 550°C, one specimen with $0 \le R \le 0.8$ and one with $-1 \le R \le 0$. The choice of constant K_{max} minimizes the effects of interactions between plastic zones from the different steps [1,2]. The applied loading sequences, in terms of maximum and minimum stresses normalized by the maximum stress, are shown schematically in Fig. 1(a). The applied sequences were chosen to give at least 0.1 mm increment

during each step, as calculated from the calibration curve, corresponding to ten data points per load step since the resolution is 0.01 mm. Figure 1(b) shows the actually recorded data points. For longer crack lengths (i.e. higher K) less than ten data points are recorded as the crack growth is too fast in relation to the frequency of recording. In essence, each step is evaluated as a separate FCG test. Note that due to low load levels during the tests with positive R-values, the lowest set of data points for R=0.8 ended up in the near-threshold region, and could therefore not be used in the subsequent evaluation.
For comparison previous results from conventional testing at R=0, 0.6 and 0.8 on the same material and under identical conditions were used. For each R-value, two specimens were tested to generate data in the Paris regime plus one specimen to evaluate the fatigue crack growth threshold. It should be noted that if the discarded near-threshold data for the first R=0.8 step from the varying R test is compared to the data from the conventional threshold level test they coincide perfectly.

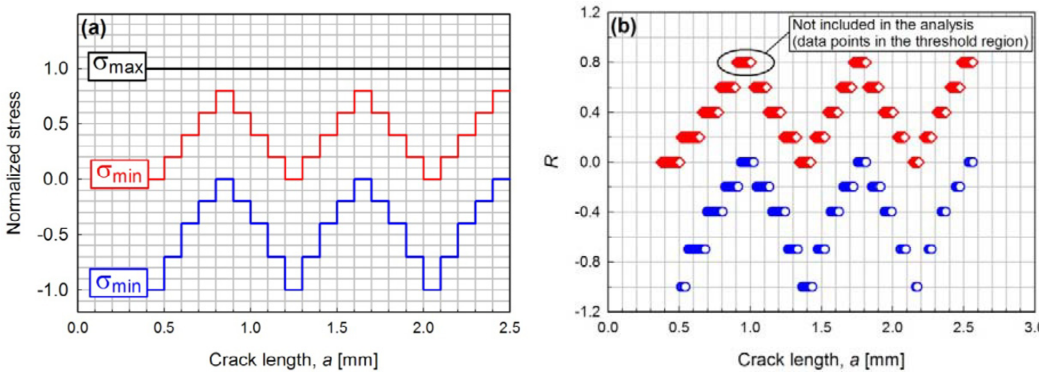


Figure 1. (a) Schematic view of the applied maximum and minimum stresses in the tests, normalized by the maximum stress (same in both tests), as a function of crack length. (b) Resulting measured data points in terms of R-values vs crack length.

3. RESULTS

Figure 2(a) shows the results for R=0, 0.6 and 0.8 from the tests with varying R and the data from the corresponding conventional tests. There is a good agreement between the data, but the scatter is bigger in the tests with varying R. To quantitatively analyze the results, the NASGRO™ equation (here without the term describing the near-fracture region) is used [5]:

$$\frac{da}{dN} = C\left[\frac{1-f(R)}{1-R}\Delta K\right]^n \left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p \qquad (2)\#$$

The crack opening function is given by

$$f = \frac{K_{op}}{K_{\max}} = \begin{cases} \max\left(R,\, A_0 + A_1 R + A_2 R^2 + A_3 R^3\right) & , R \geq 0 \\ A_0 + A_1 R, & -2 \leq R < 0 \end{cases} \qquad (3)$$

where

$$A_0 = \left(0.825 - 0.34\alpha + 0.05\alpha^2\right)\left[\cos\left(\pi S_{\max}/2\sigma_0\right)\right]^{1/\alpha} \qquad (4a)$$

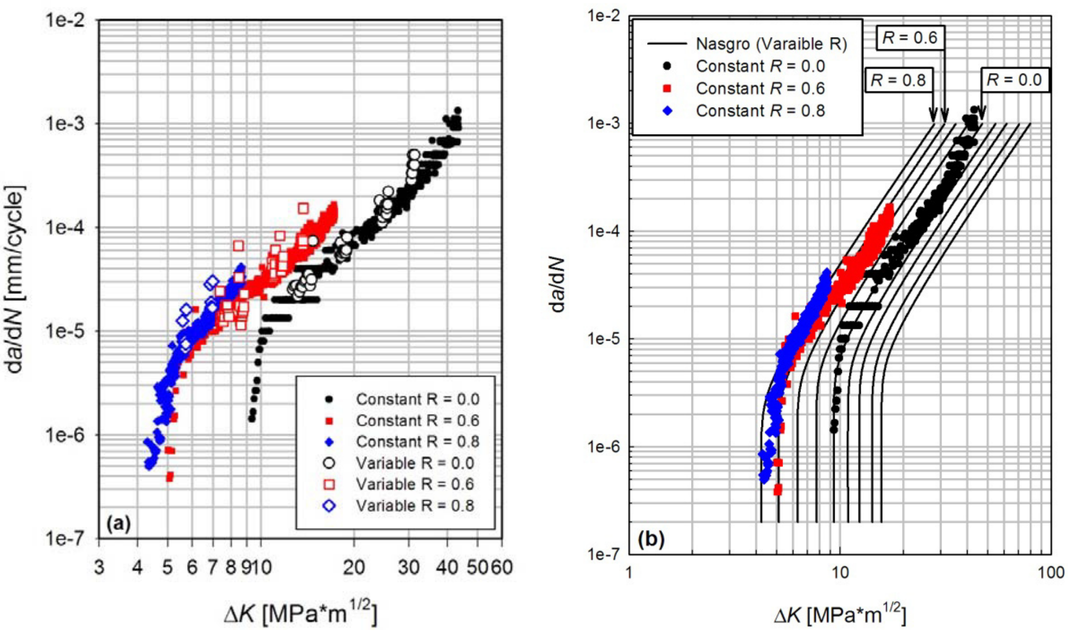
$$A_1 = \left(0.415 - 0.071\alpha\right)\left(S_{\max}/\sigma_0\right) \qquad (4b)$$

$$A_2 = 1 - A_0 - A_1 - A_3 \qquad (4c)$$

$$A_3 = 2A_0 + A_1 - 1 \qquad (4d)$$

In the present investigation, the constraint factor, α, is used as a fitting parameter whereas σ_{max}/σ_0 is treated as a constant, set to 0.3 in accordance with the NASGRO manual [5]. As no data is available in the near-threshold region for the varying R tests, p was treated as a constant and was set to 0.25. The constants C, n and α were determined by regression analysis using data from conventional and varying R tests separately to obtain two sets of parameters. Additionally, constants in the expression for the R-dependence of the threshold level [5] were determined using data from separate conventional threshold level testing (with $C^{th}{}_{m}$=0.1). The result of the fitting of Eq. (2) to the varying R tests can be seen in Fig. 2(b) together with the data from conventional testing. As can be seen there is a very good agreement between the varying R predictions and the conventionally generated data.

The FCG curves, a vs N, were calculated for the specimen geometries and loading conditions applied in the conventional test series, using NASGRO 5.21 and the data obtained from regression analysis of the results from both test methods separately. As NASGRO calculates the growth of a (the deepest point) and c (the surface intersection points) separately, with free surface retardation of the c-tip, the crack lengths were taken as the average of the calculated values of a and c at a given cycle. The results are shown in Fig. 3, where the calculated crack growth curves up to a crack length of 2 mm (normalized by the experimentally observed number of cycles N_{exp} at a=2 mm) are shown. Figure 4 shows the ratio of calculated number of cycles to reach a=2 mm (N_{calc}) to N_{exp}. The crack growth lives predicted by the data from the varying R tests were shorter than the predicted lives based on conventionally generated data in all cases. Generally, both methods yielded conservative predictions. The worst precision was observed for R=0.8, where the predicted lives where in the range 0.6-0.7 of the experimentally observed values. For R=0 and 0.6 the precision was better than 20% of the observed crack growth life.



(a) **(b)**

Figure 2. (a) Comparison between the experimental data from conventional and varying R tests for R=0, 0.6 and 0.8; (b) Predicted da/dN-ΔK curves from Eq. (2) based on the varying R test compared to the experimental data from the conventional tests.

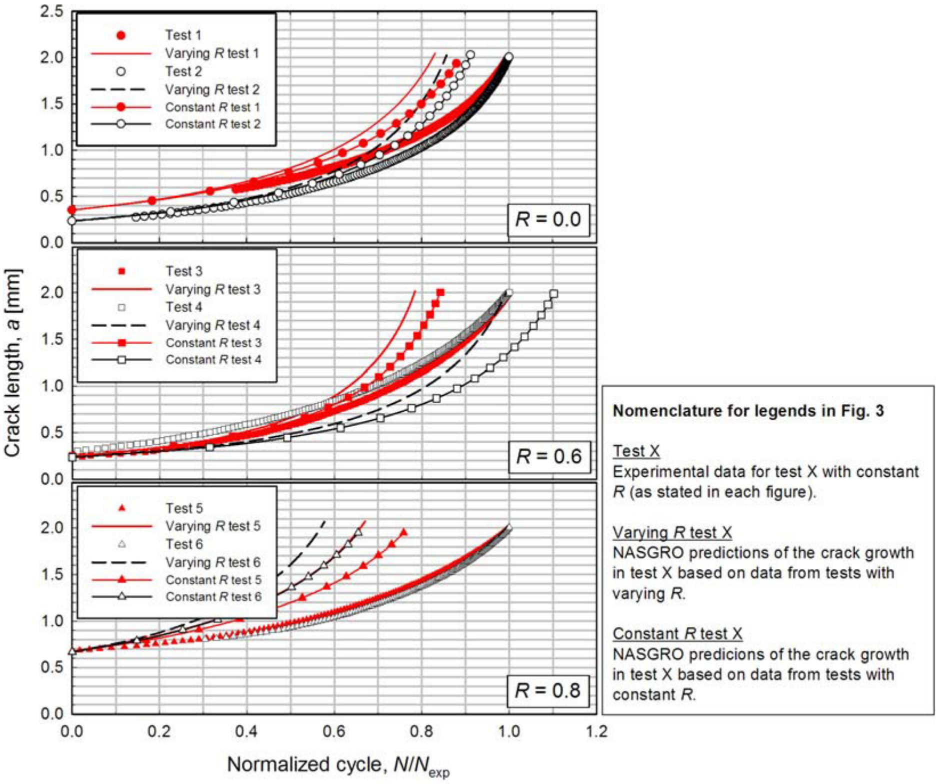


Figure 3. Calculated normalized FCG curves using Eq. (2) and the parameter sets obtained from the varying R and conventional tests as compared to the experimental data from the conventional tests.

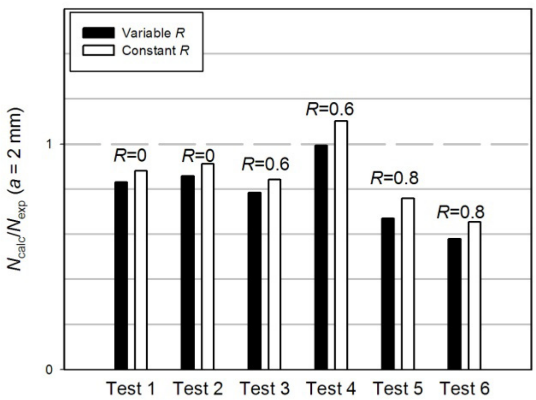


Figure 4. Fraction of calculated to experimental number of cycles to reach a=2 mm for the two methods.

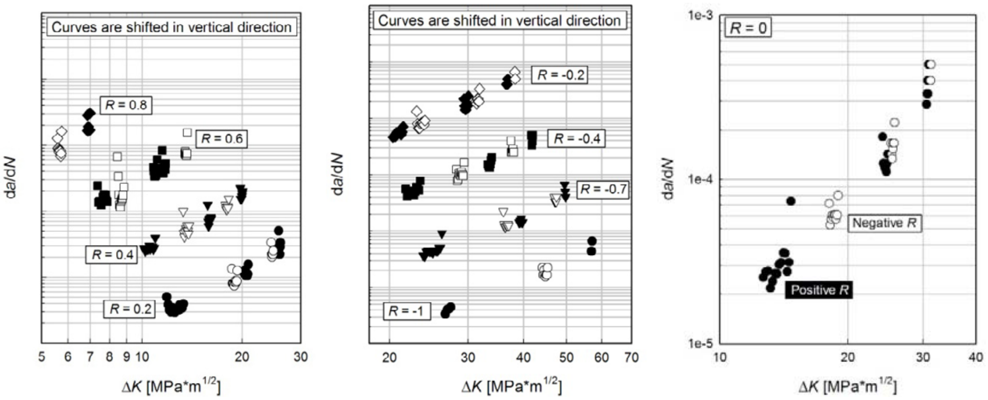


Figure5. (a) Comparison of the parts of the test with increasing (closed symbols) and decreasing (open symbols) Pmin for the test with positive R-values. (b) as in (a) but for the test with negative R-values. (c) Comparison of the results for R=0 from the two tests.

4. DISCUSSION

One concern was that the data from the parts of the tests with increasing $P_{\min}$ would give different results compared to parts with decreasing $P_{\min}$ due to the interactions of the plastic zones from the successive steps. However, as can be seen in Fig. 5(a) and (b), no such effect could be observed. Figure 5(c) shows that the d*a*/d*N* data from the steps with *R*=0 in the two tests also coincide very well. This gives some confidence that the method is self-consistent.

The scatter in the varying *R* method is appreciably larger compared to the conventional testing. By examining data from the individual steps it can be seen that the scatter is mainly constituted of the first and/or last data point in the step having considerably higher values than the remaining points. One possible explanation could be the change in the plastic zone size with change in *R* which could result in a transient behavior at the beginning of a step [2].Such an effect would manifest itself as a initially low d*a*/d*N* in the steps with increasing *R*, which increases towards the steady state rate. Similarly, in steps with decreasing *R*, the initially measured d*a*/d*N* values would be too high, but decrease towards the steady state. In the present results, such behavior is not observed. The deviating initial data points are (almost) always higher than the steady state rate, irrespective of increasing or decreasing *R*-values. Furthermore, this effect could not explain the fact that also the last data point in several steps is also higher than expected. It must, however, be said that the higher scatter observed is a drawback of the varying *R* method. One way to handle this is to discard the initial (and possibly final) data point in each step. A more rigorous approach would be to calculate the change in plastic zone size upon stepping (as a function of *R* and *a*) and discarding the data points which are expected to fall within the calculated transition zone.

5. CONCLUSIONS

- The present method, using constant $P_{\max}$ and step-wise varying *R* during a test, was successfully applied to determine the *R* dependence of the FCG behavior of specimens with a limited crack length in a time efficient fashion..
- The FCG predictions of the conventional tests based on data from both the conventional and varying *R* tests showed that there is no significant difference between the two methods.
- No significant effects of interactions between the plastic zones from the successive steps. In this respect, no difference was seen between the parts of the tests with increasing and decreasing $P_{\min}$.
- The scatter was larger in the varying *R* method compared to the conventional tests and the measured FCG rates were somewhat higher. How much of this is test method related and how much is variation between specimens is not clear at present.

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